

Field Quality Issues in the Solenoid for Electron Cooling in RHIC

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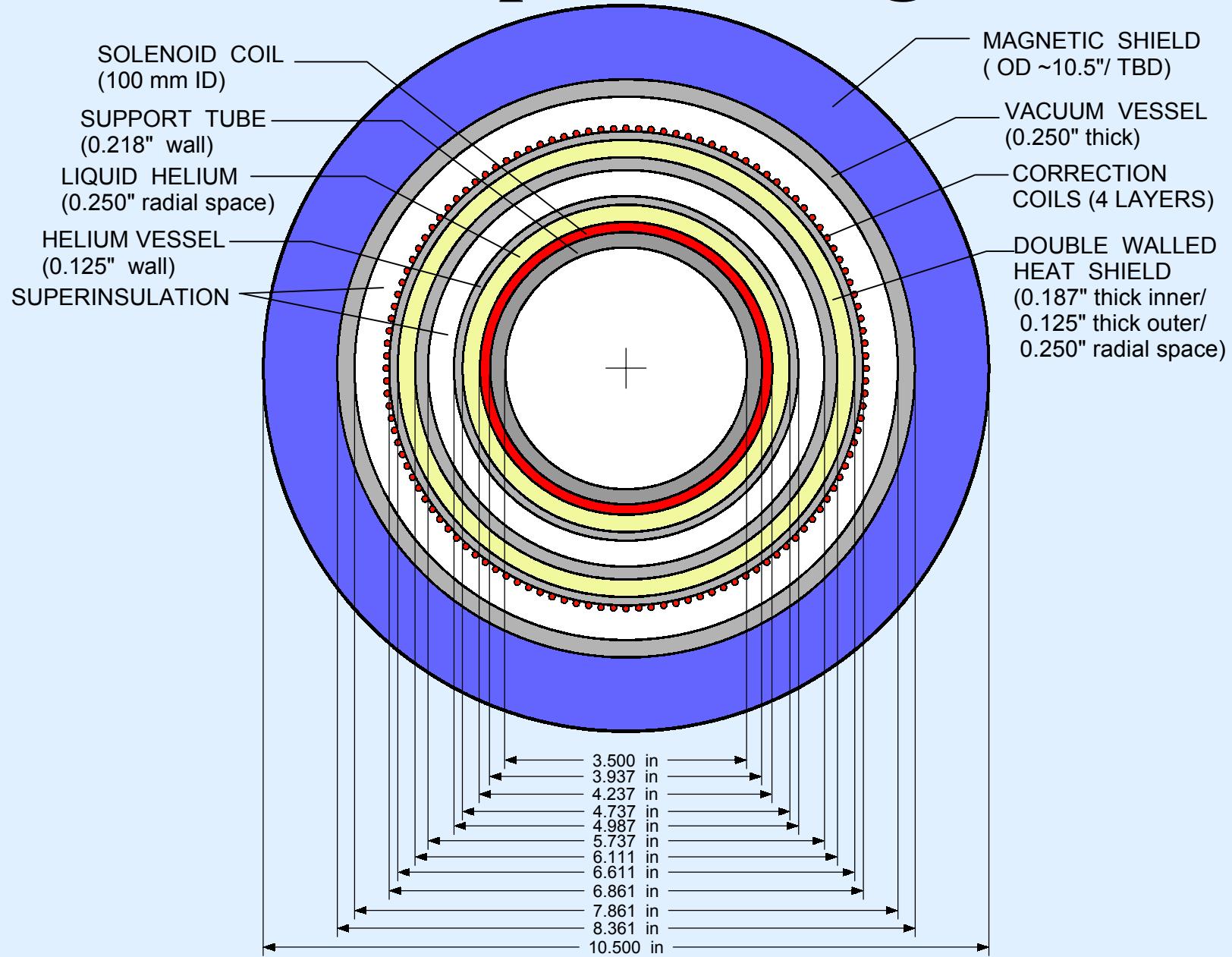
Outline

- Basic requirements.
- Conceptual design of Solenoid
(Conductor choice)
- Dipole correction coils
(Design, achievable correction level)
- Magnetic measurements
(Perhaps the most challenging aspect!)

Basic Solenoid Requirements

- 1 Tesla axial field (> 1 T preferred?)
- Up to 30-meter total length (perhaps in two or more sections)
- 100 mm coil ID (gives approx. 89 mm cold bore diameter; warm bore needed?)
- $B_{\perp} / B_{axial} \leq 1 \times 10^{-5}$ (on-axis \Rightarrow straightness)
(How about off-axis? At least ~ 5 mm radius zone is needed just to make measurements.)

Conceptual Design



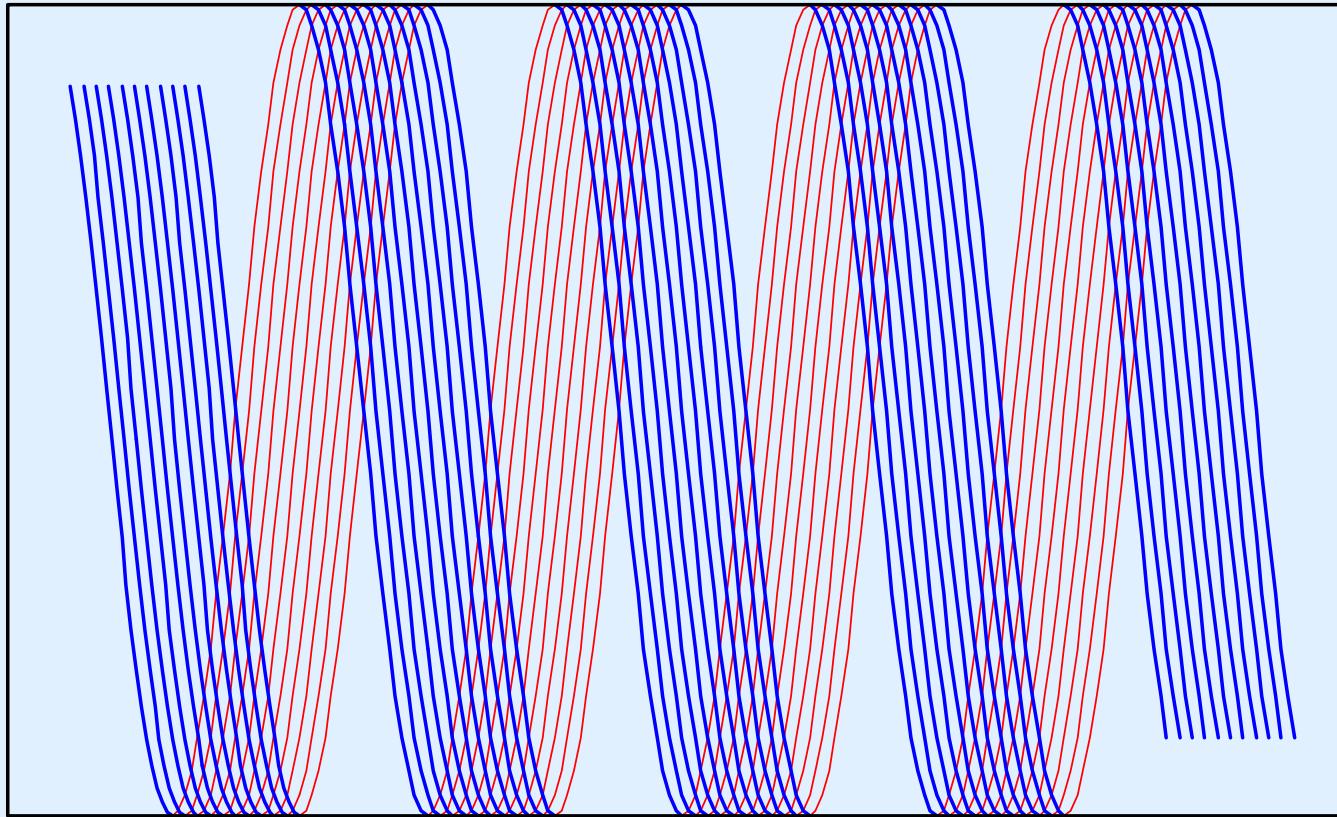
The Solenoid Coil

- Use even no. of layers to bring leads out at a single end.
- Use only 2 layers to minimize complexity
 - ⇒ Current for 1 T $\sim 400 \times \text{pitch(mm)} \text{ Amps.}$
 - ⇒ Inductance $\sim 39.5 / [\text{pitch(mm)}]^2 \text{ mH/meter}$
- An earlier design favored a RHIC dipole type flat cable ($\sim 10 \text{ mm pitch}$) to keep the inductance low.
- Field quality considerations suggest that a smaller pitch is preferable.

Winding Pitch Vs. Field Quality

- An ideal solenoid has strictly azimuthal current loops and produces zero transverse field on the axis.
- A real solenoid is wound with a finite pitch, destroying the azimuthal symmetry. This produces transverse fields, even on-axis.
- Larger pitch produces larger transverse fields.
- Opposite pitch in the second layer helps to compensate most of the transverse field, but it is not a perfect cancellation.

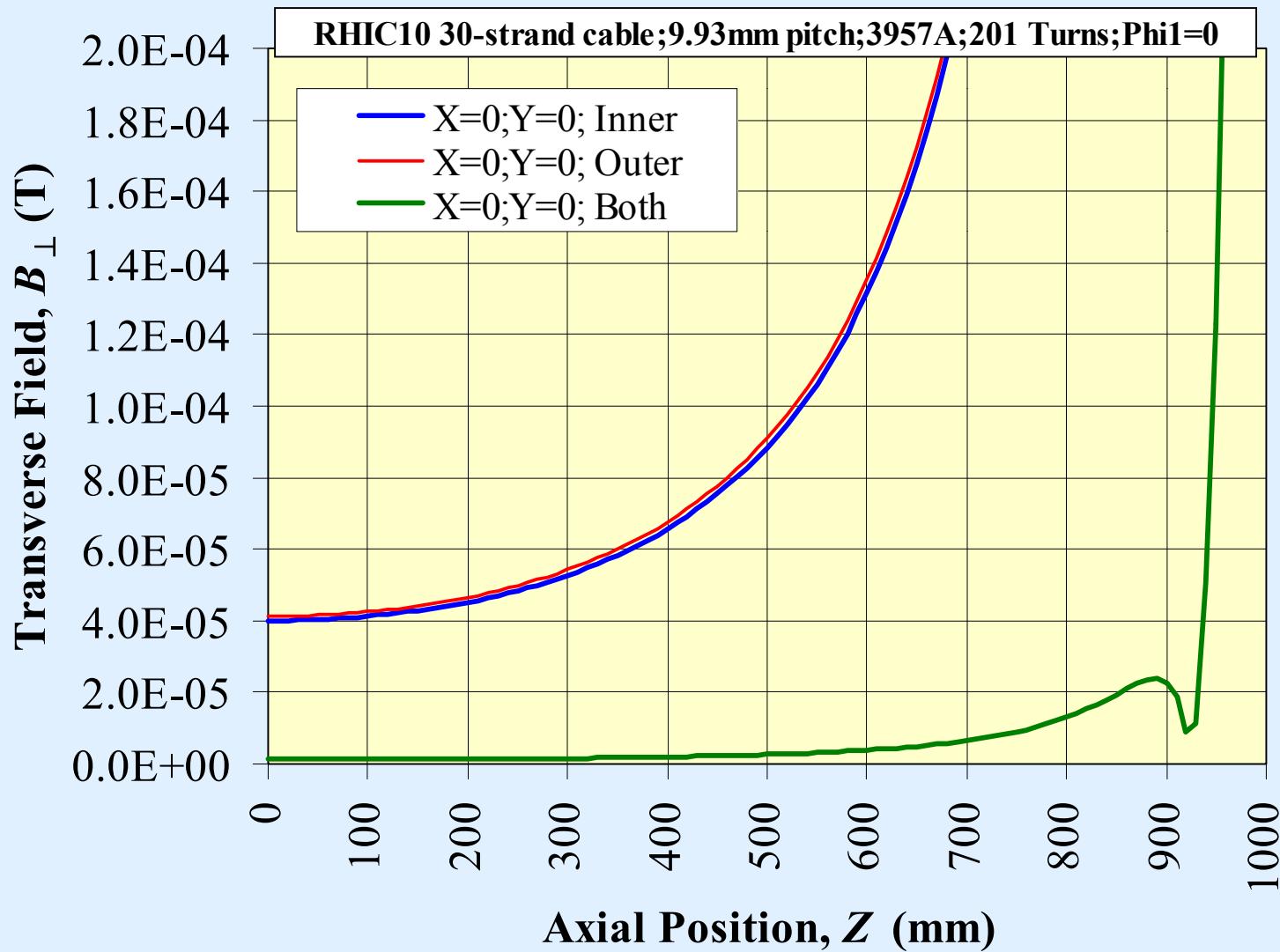
Winding with a Finite Pitch



Tilt angle (from vertical) $\sim 0.5 \times$ Pitch/diameter
Pitch must be \geq Cable width

B_{\perp} with RHIC 30 Strand Cable

Pitch = 9.93 mm; $I = 3957 \text{ A}$; $L = 0.4 \text{ mH/meter}$

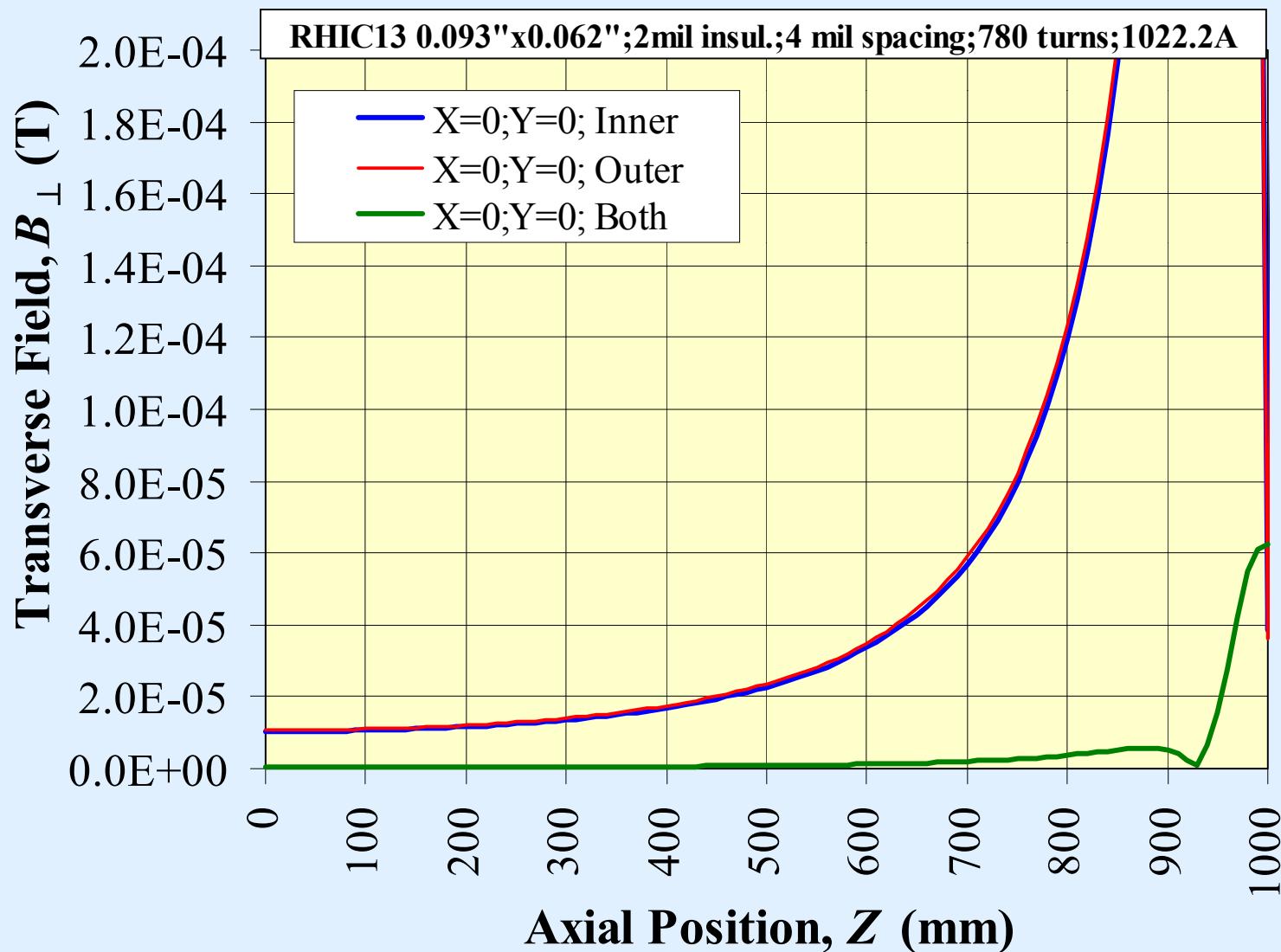


Optimal Conductor Choice

- Smaller conductor size could produce a better field quality, but increases inductance and reduces quench margin.
- It is desirable to have sufficient copper in the conductor to handle a quench at the maximum possible field (J_{Cu} at quench $\leq 1000 \text{ A/mm}^2$.)
- Wires of rectangular cross section are preferred over circular cross section for multilayer solenoids.
- An inexpensive, off-the-shelf, $0.093'' \times 0.062''$ wire with Cu:Sc ratio of 7:1 has been found to be appropriate.

B_{\perp} with $0.093'' \times 0.062''$ Wire

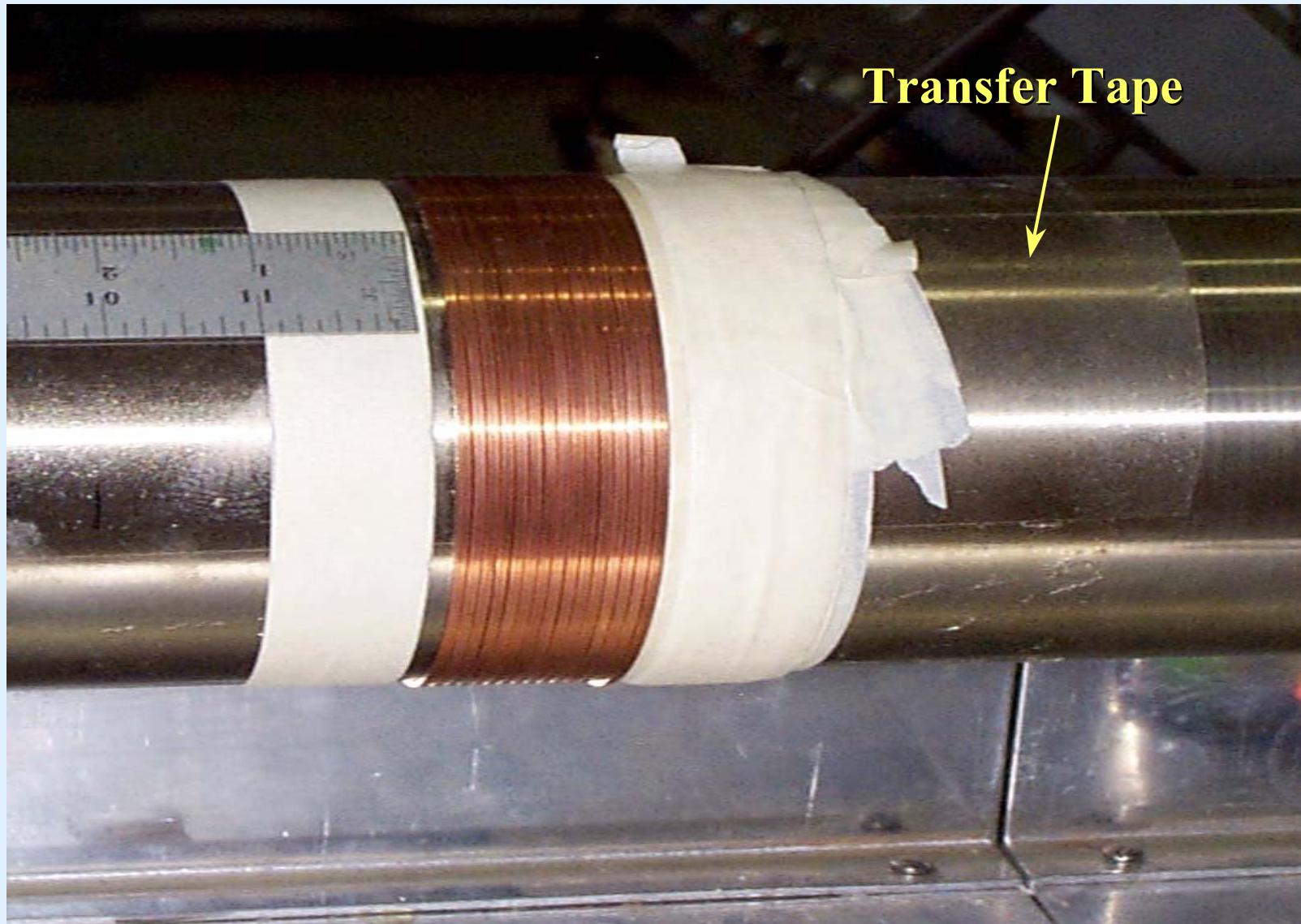
Pitch = 2.565 mm; $I = 1022$ A; $L = 6.2$ mH/meter



Comparison of Various Conductors for e-Cool Solenoid

Parameter	RHIC Single Strand	0.093" × 0.062" Wire	RHIC 30 Strand Cable	RHIC 36 Strand Cable
Width (mm)	0.648 dia.	2.362	9.73	11.68
Thickness (mm)		1.575	1.17	1.16
Cu:Sc Ratio	2.25	7.0	2.25	1.8
Winding Pitch (mm)	0.85	2.565	9.93	11.88
I at 1 T (A)	340	1021	3951	4727
L (mH/meter)	56.1	6.17	0.41	0.29
$ B_{\perp} $, Center, each layer (T)	3.4×10^{-6}	1.0×10^{-5}	4.0×10^{-5}	4.8×10^{-5}
I_{Quench} (A)	511	2017	10309	13197
B_{Quench} (T)	1.51	1.98	2.61	2.79
Current Margin	51%	97%	161%	179%
J_{Cu} at 1 T (A/mm ²)	1483	314	577	619
J_{Cu} at Quench, A/mm ²)	2238	620	1505	1729

Test Winding with 0.093"×0.062" Wire



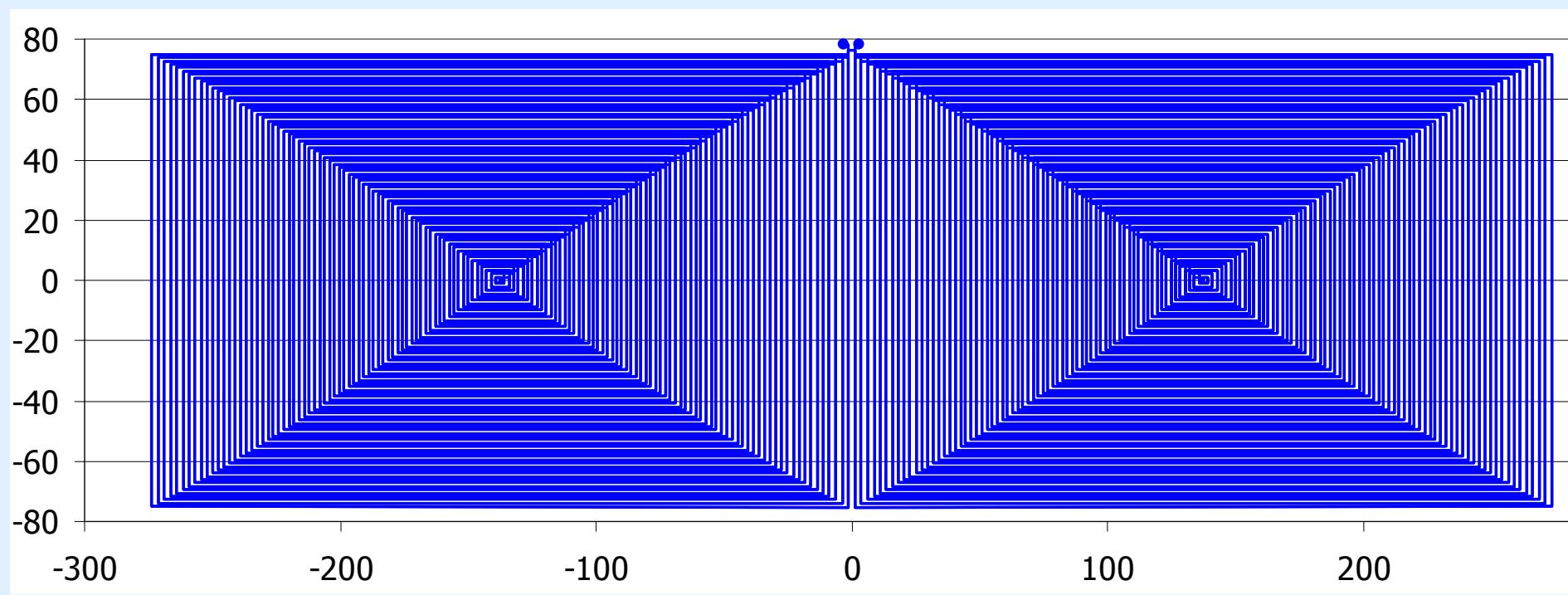
Dipole Correction Coils

- $B_{\perp}/B_z \sim 10^{-5}$ implies a straightness of $10 \mu\text{m}$ over 1 meter length. This may not be achieved with mechanical alignment alone.
- Winding imperfections are also likely to produce transverse fields on-axis.
- Goal is to achieve as close to 1×10^{-5} as possible with construction tolerances and mechanical adjustment (expect $\sim a \text{ few} \times 10^{-4}$)
- Correct the remaining errors with an array of dipole correction coils.

Dipole Correction Coil Design

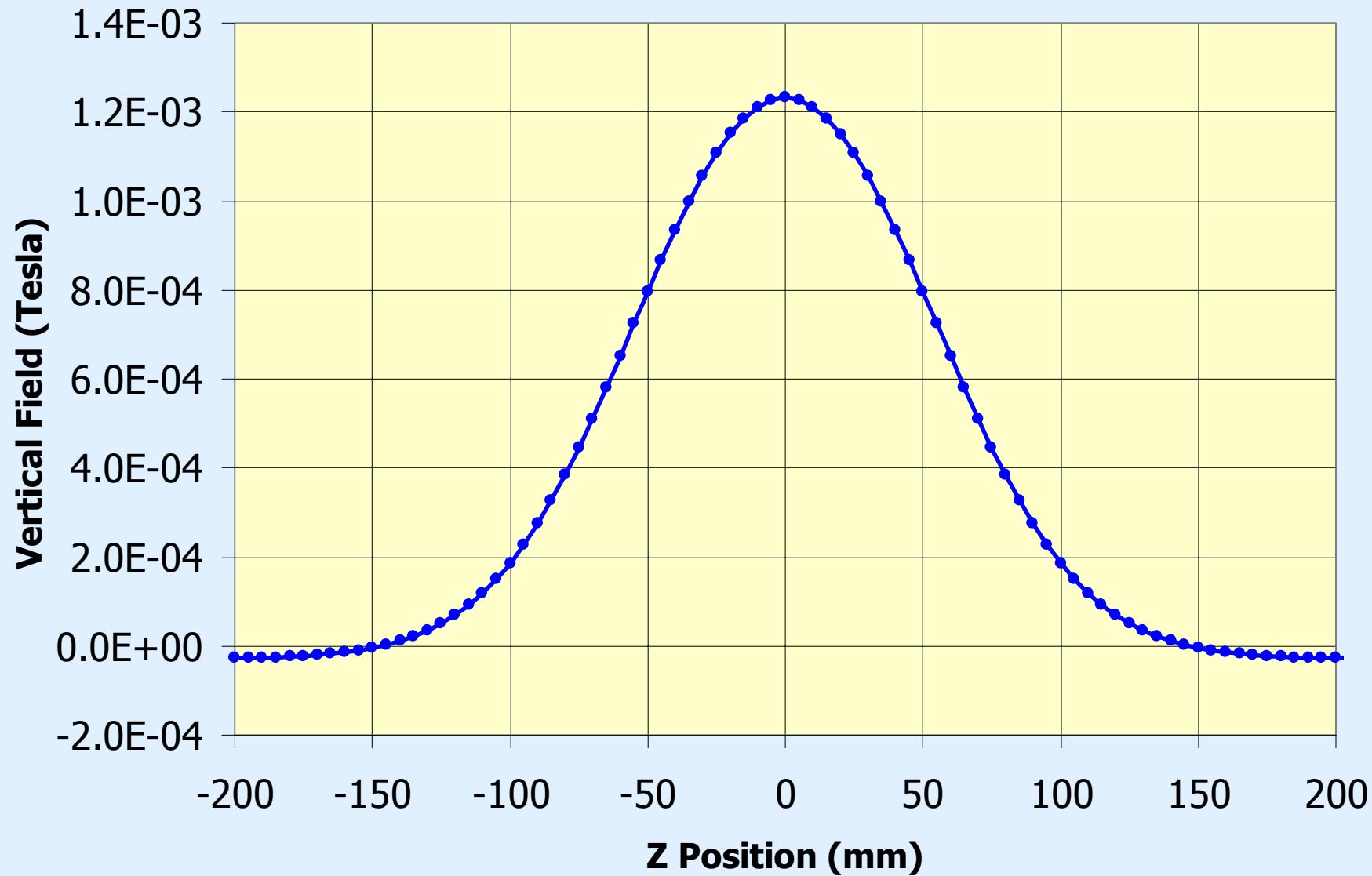
- Typical length scale for field variation \sim coil diameter = 100 mm.
- Need an array of very short dipoles (Length less than diameter, Field $\sim 10^{-3}$ T at $\sim 2A$)
- Printed circuit dipoles, with purely azimuthal end turns, could provide an inexpensive way of building such correction elements [used at Univ. of Maryland, *W.W. Zhang, et al., PRST-AB, Vol. 3, 122401 (2000)*]
- An algorithm is developed to design such coils with both poles in the same circuit board.

A Typical Dipole Correction Coil

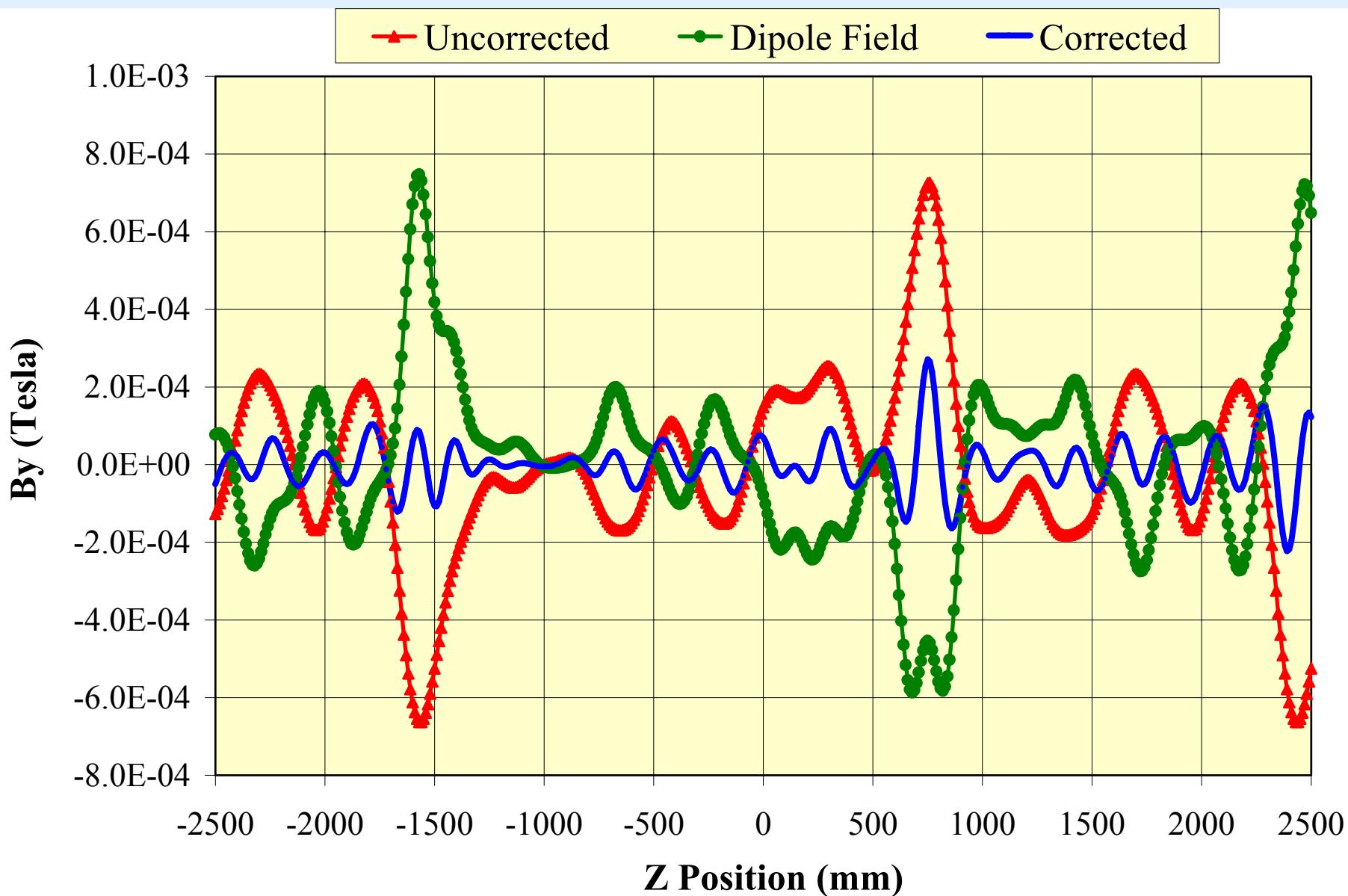


175 mm diameter; 150 mm length; 68 turns/layer
0.9 mm wide patterns; 0.2 mm gap between lines; 2 layers
~ zero integral harmonics
 1.2×10^{-3} T at 2 A

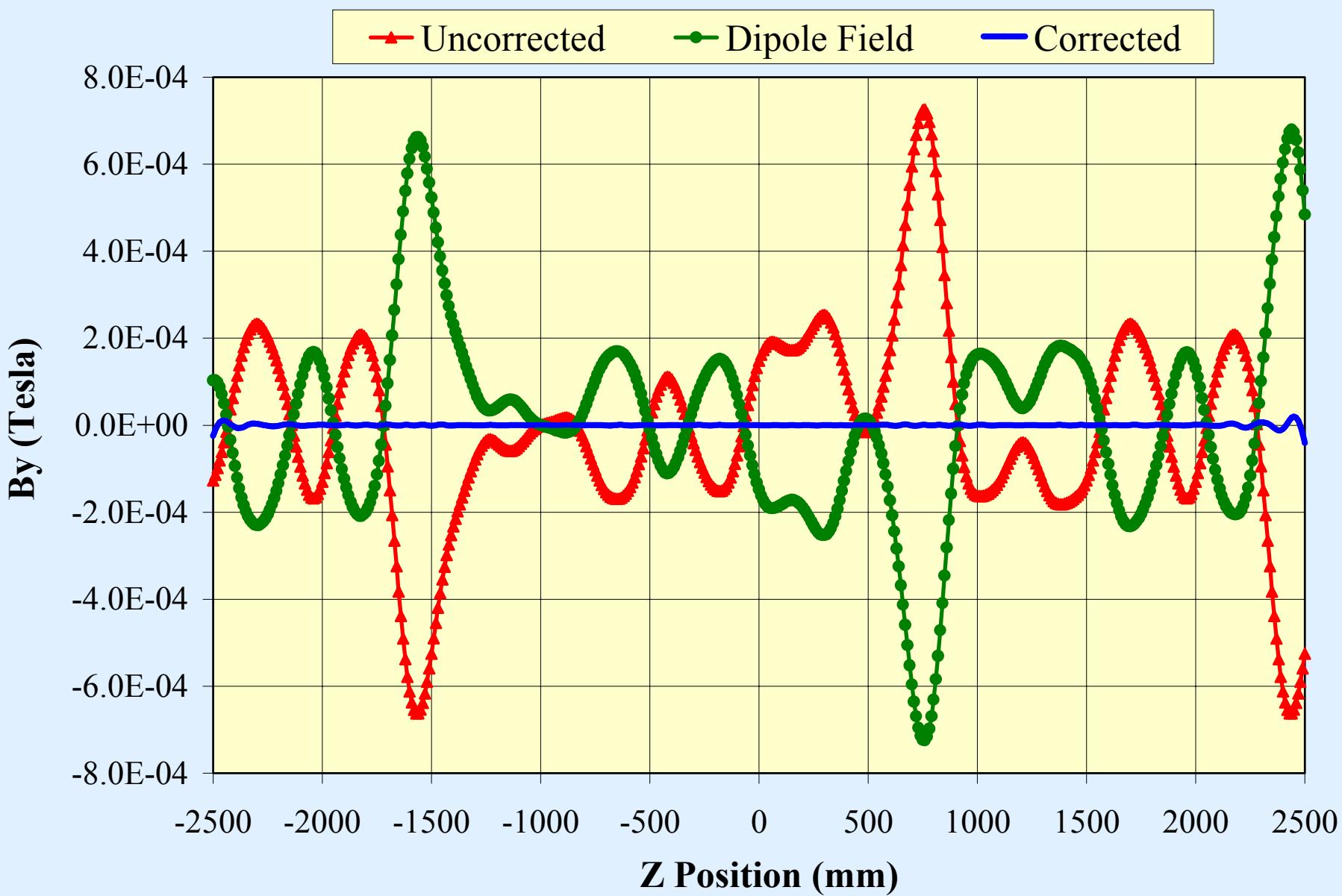
Correction Coil Field Profile (On-axis)



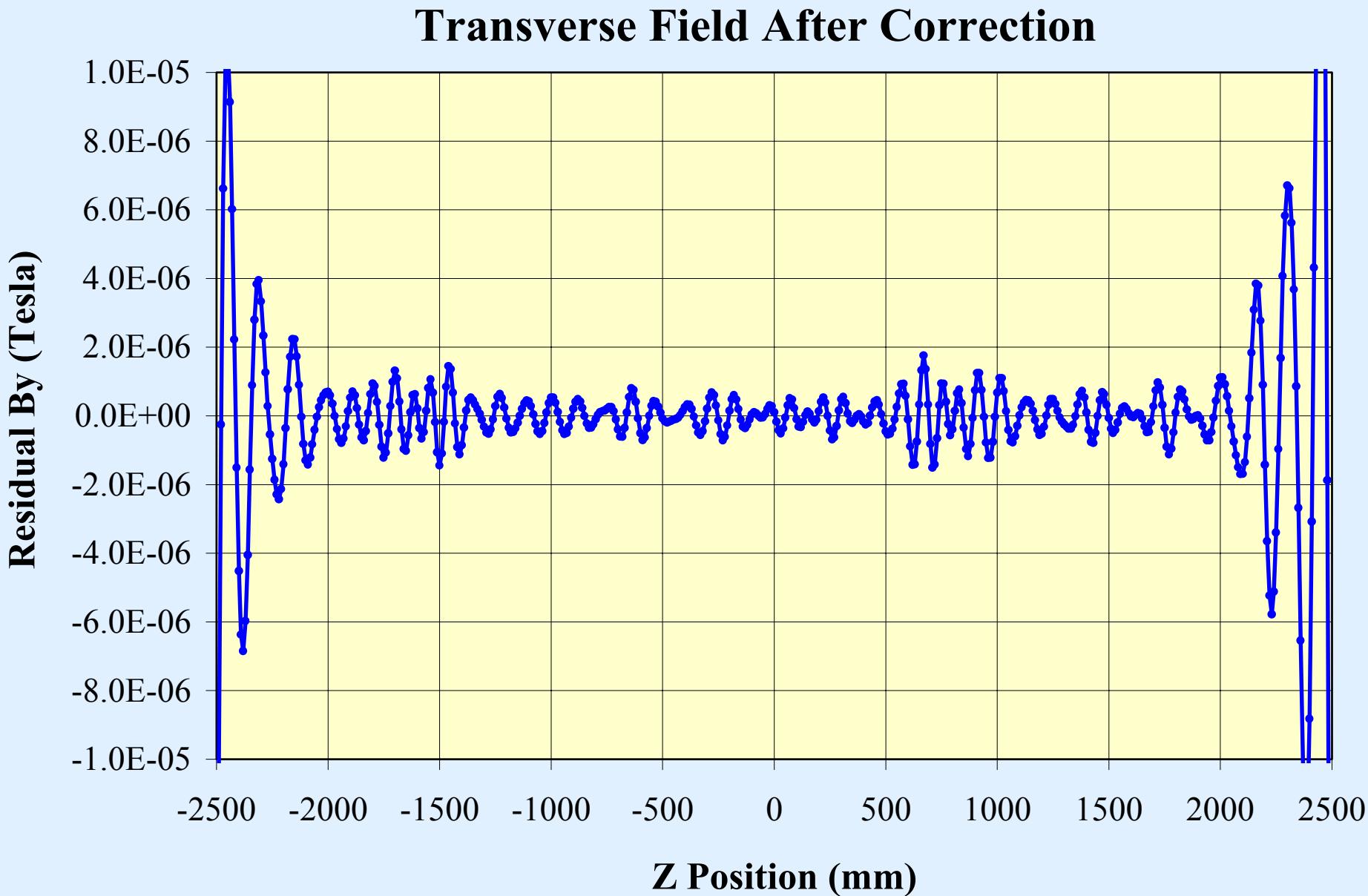
150mm pattern; 150mm pitch; single layer; *almost unphysical!*



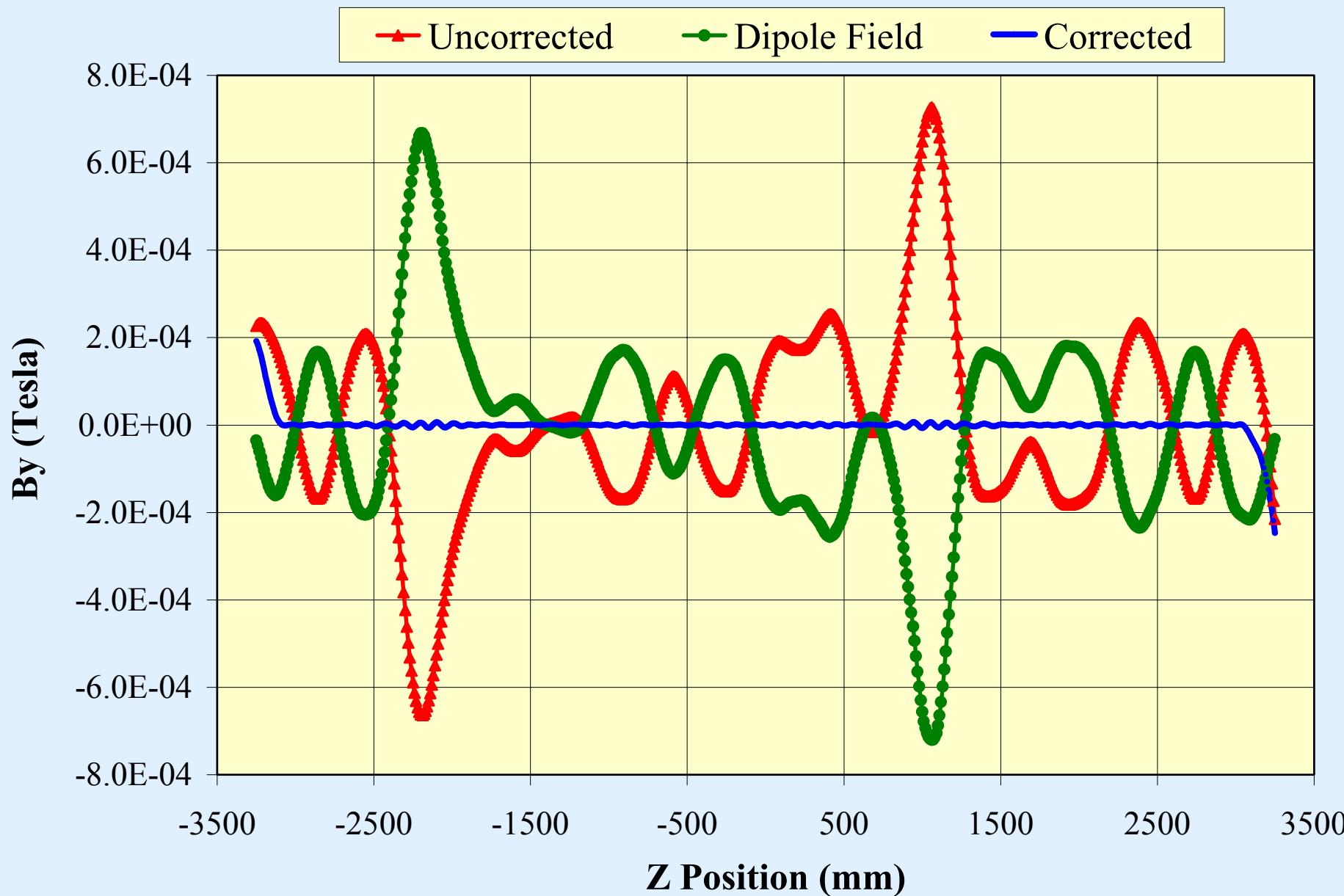
150mm pattern; 75mm pitch; single layer (VERY unphysical!)



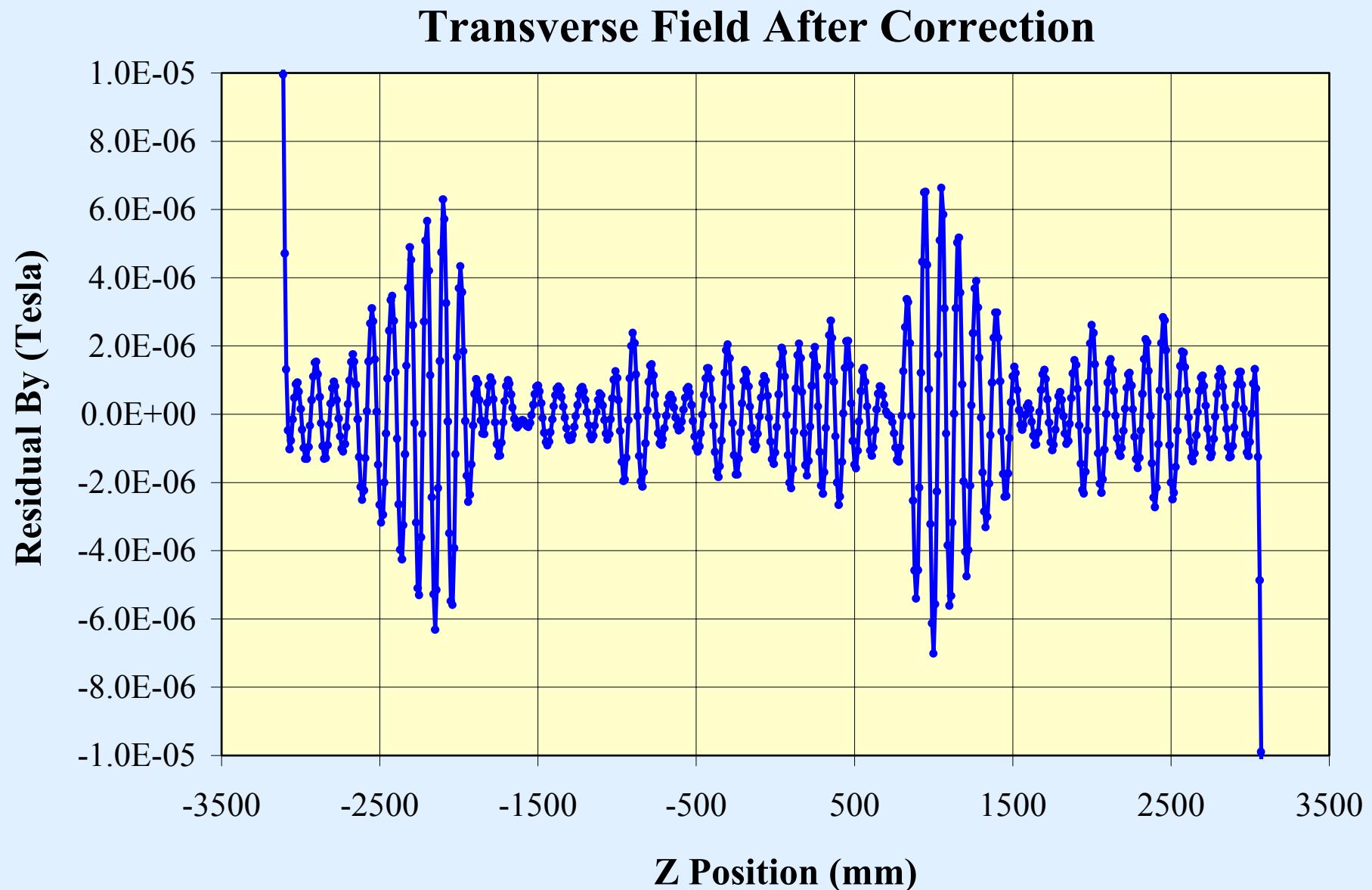
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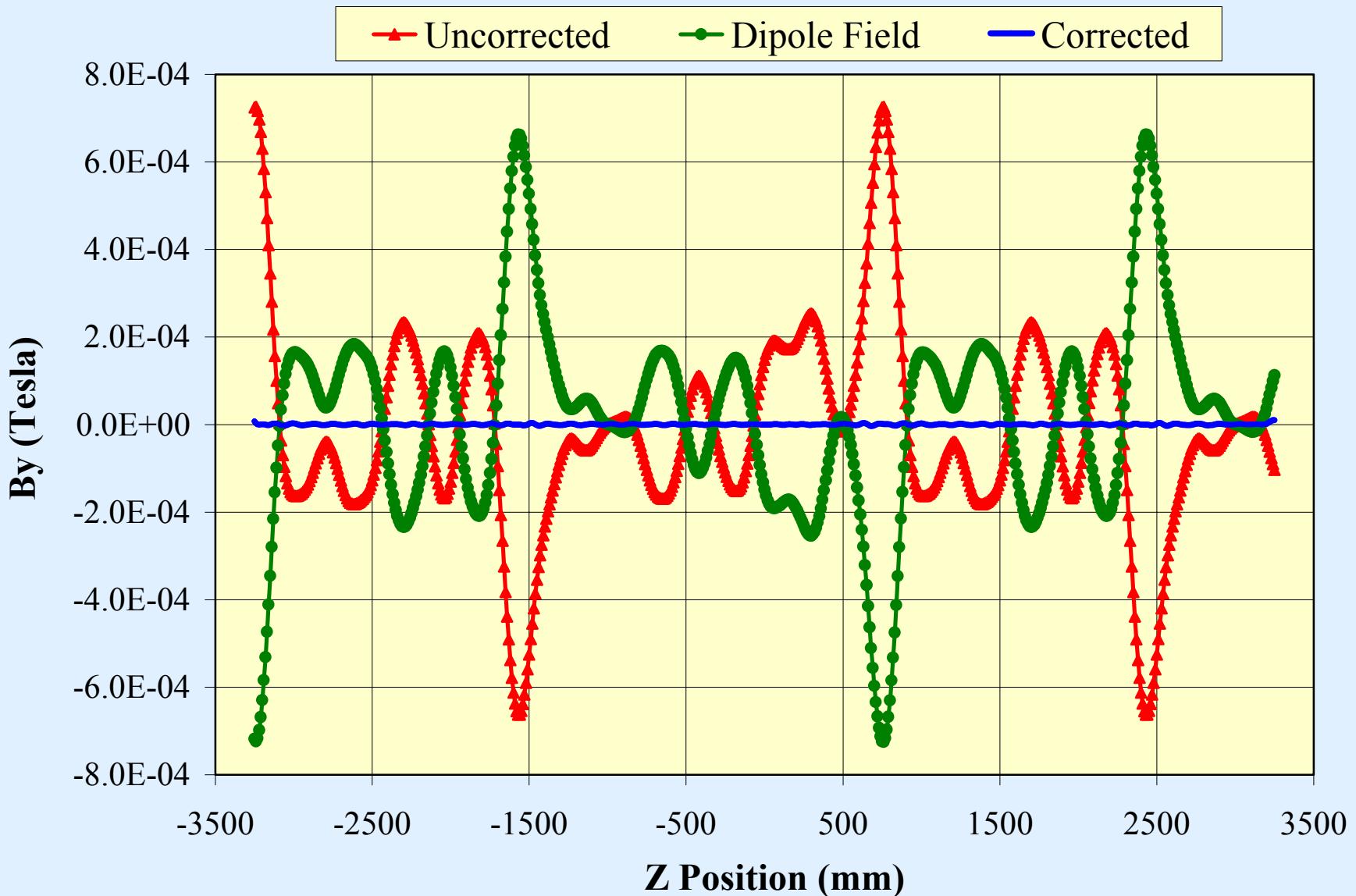
200 mm pattern; 100 mm pitch; single layer (VERY unphysical!)



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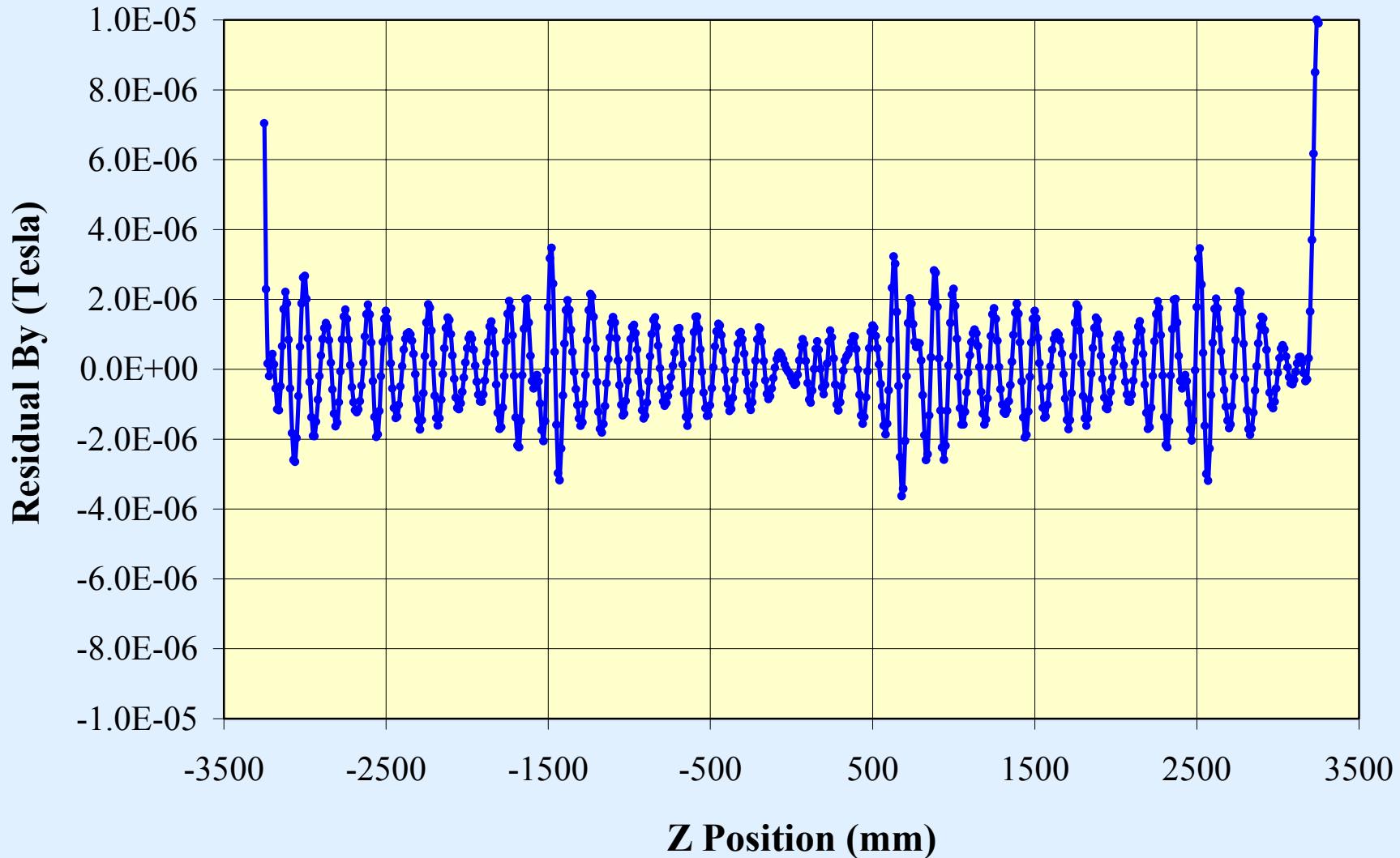


Layer 1: 150 mm pattern; 160 mm pitch; 174.8 mm ID
Layer 2: 150 mm pattern; 160 mm pitch; 186 mm ID
Layer 2 offset axially by 80 mm



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Transverse Field After Correction

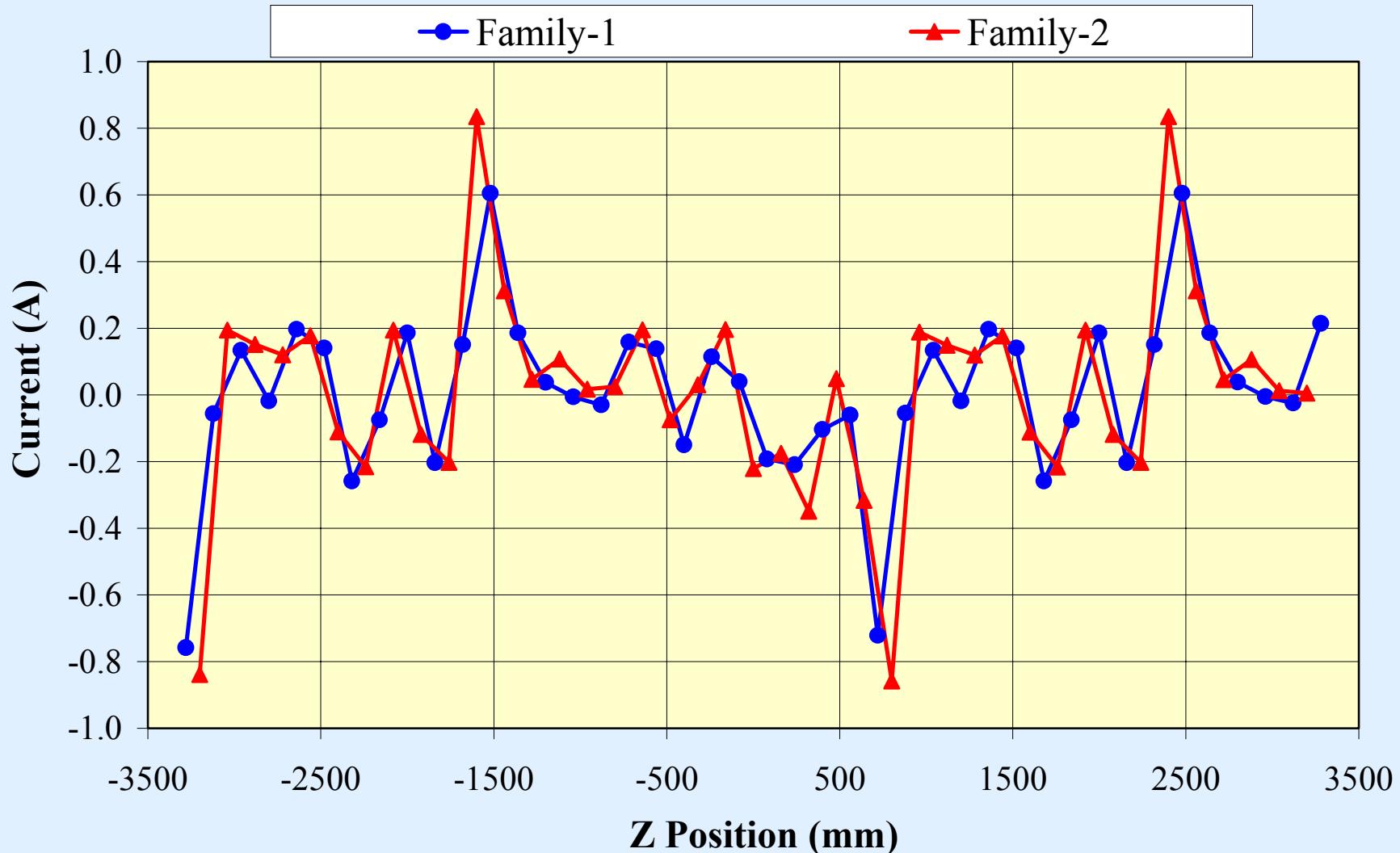


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Currents in Various Dipole Circuits

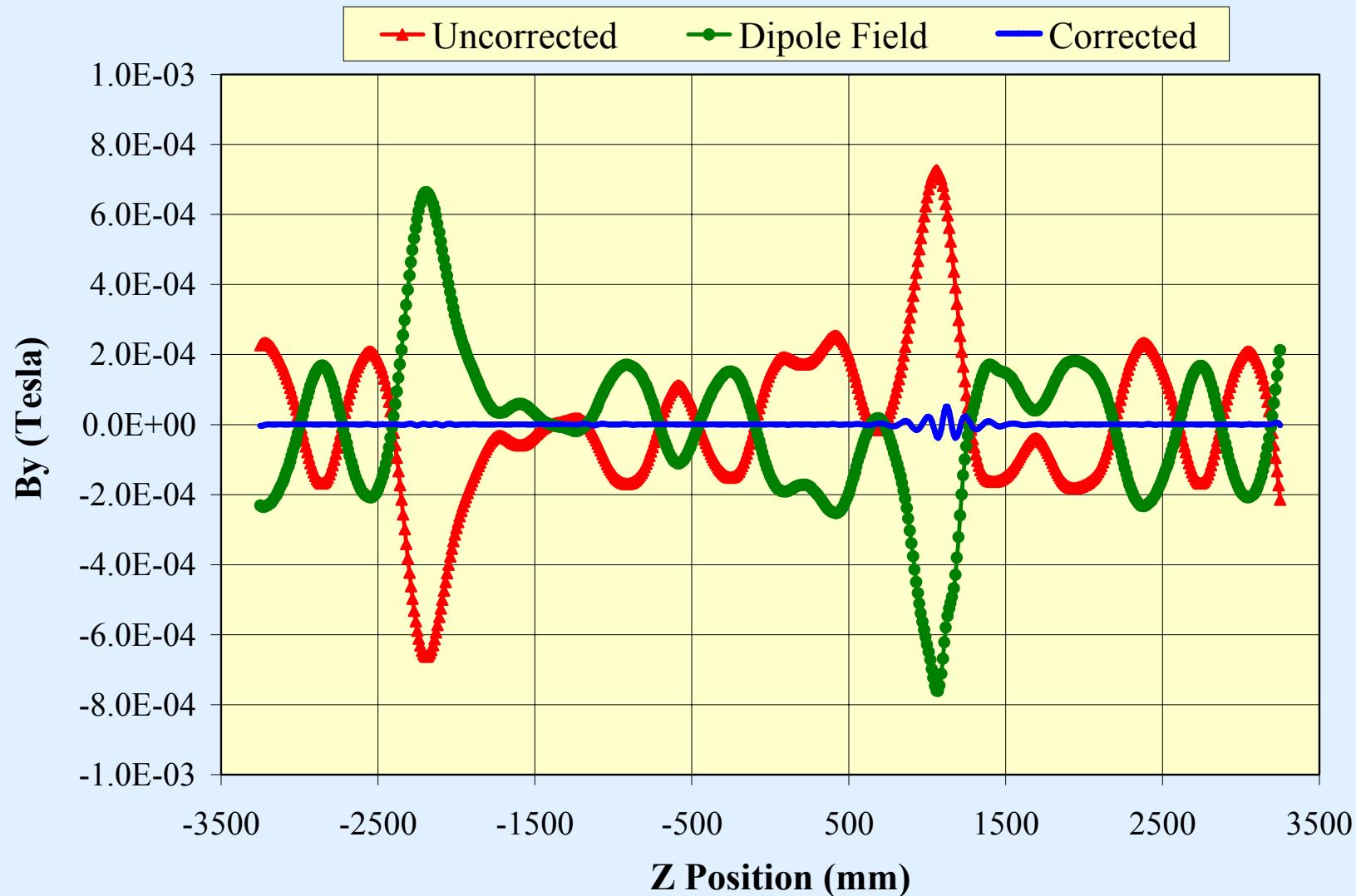


Family 1: 150 mm patterns; 160 mm pitch; 174.8 mm ID

Family 2: 150 mm patterns; 160 mm pitch; 186 mm ID; Offset 80 mm

~ 2 m long segments with 10 mm gaps for supports

Family 3: 70 mm patterns; 186 mm ID; fills ends of sections



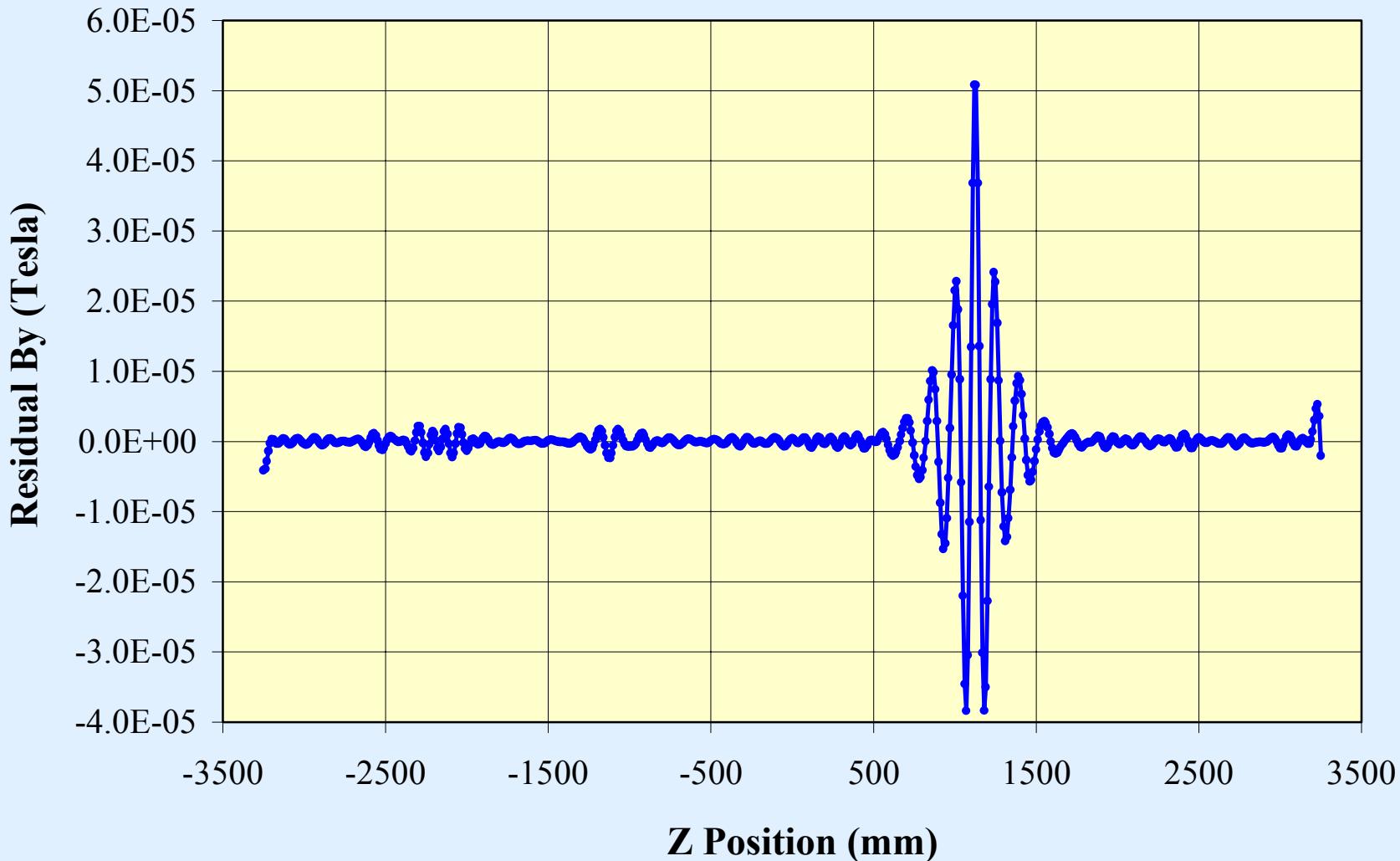
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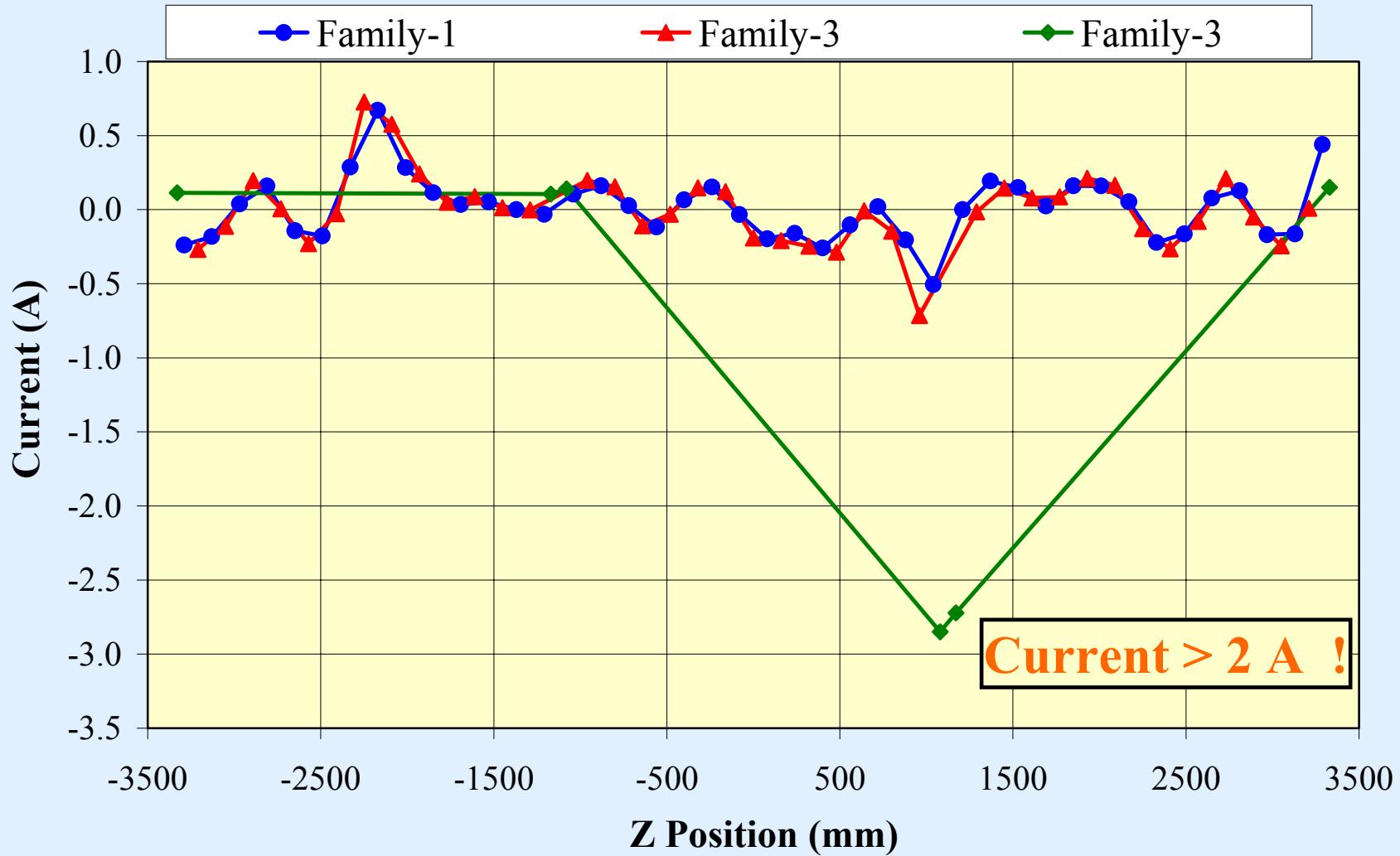


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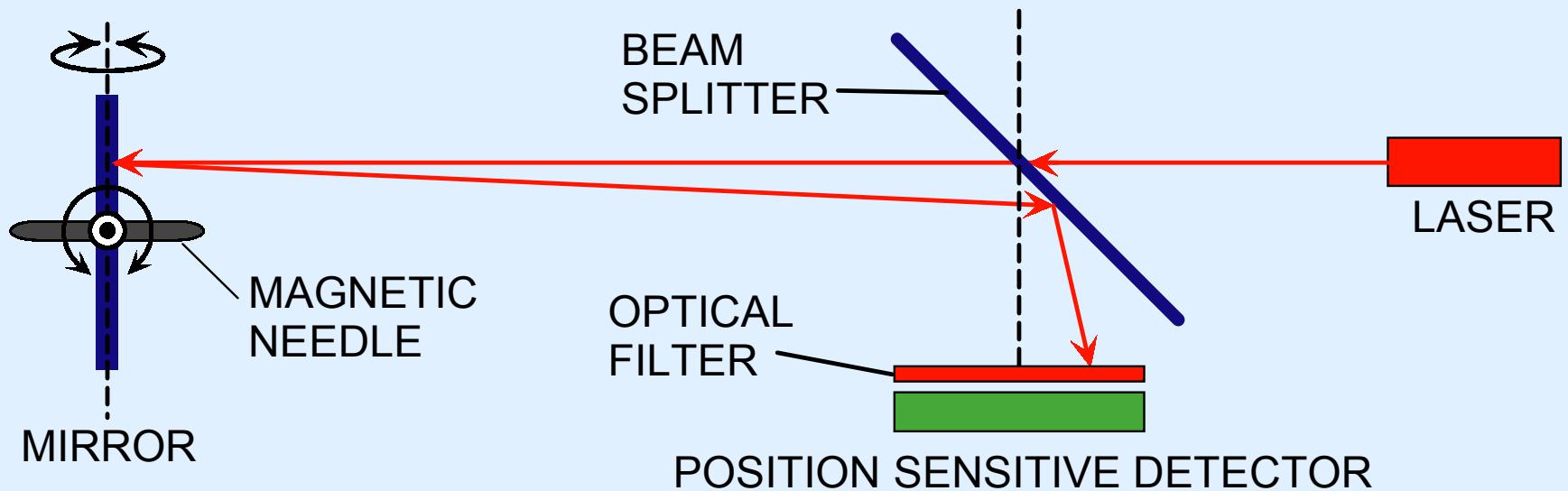
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Currents in Various Dipole Circuits



Magnetic Measurements



(Based on *C. Crawford et al., FNAL and BINP, Proc. PAC'99, p. 3321-3*)

- Expected resolution $\sim 10^{-5}$ radian, just enough to achieve $B_{\perp}/B_z \sim 10^{-5}$. Better techniques?
- Field quality on the test stand Vs. field quality in the as-installed magnet? Alignment Stability?

Conclusions

- Solenoidal field of 1 T can be achieved with a variety of conductor options. All options have ample margins.
- Field quality is likely to be better with smaller winding pitch. A 2.4 mm wide rectangular conductor is chosen for the prototype.
- Printed circuit dipoles, \sim 150 mm long, should be able to correct reasonable field errors to below 1×10^{-5} level. Two layers per axis are required.
- Work is needed to design a practical support system, without introducing gaps in the layers.
- Need to study errors due to leads, iron shield, etc.
- Considerable work is needed on measurements.